Marine Pollution Bulletin 131 (2018) 347–355

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Climate change and regional human pressures as challenges for management in oceanic islands, South Atlantic

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A R T I C L E I N F O

Keywords:
Global environmental change
Coral reef
Rocas atoll
Fernando de Noronha
Marine protected area

A B S T R A C T

This study aimed to determine the main anthropogenic pressures and the effectiveness of management practices in marine protected areas (MPAs) (Rocas Atoll and Fernando de Noronha Archipelago, South Atlantic). The MPAs exhibited high management effectiveness over the last 25 years due to the control of local pressures (i.e., fishing and tourism). However, the increase in regional and global pressures, such as invasive species, marine debris, and climate change stressors (sea-level rise, extreme events, range shifts of species, warming, and ocean acidification), are environmental risks that need to be considered during conservation. Strategies for large scale marine spatial planning, as well as proposals for an integrated management of MPAs (including coral reef islands and seamounts) by the articulation of a network, which reduces regional human pressures and improves ocean governance were discussed. This study provided insights into the challenges faced in the management of MPAs in a rapidly changing ocean.

1. Introduction

Coral reefs are marine ecosystems with highly diverse species, goods, and ecosystem services (ES) (Hoegh-Guldberg et al., 2017). The importance of reefs can be highlighted by the important ES they provide, such as protection of coasts and islands against extreme waves and tides (Elliff and Kikuchi, 2017), abundance of organisms associated with trophic food webs (i.e., fishery resources) (Neubauer et al., 2013), and biogeochemical carbon balance (Rossi, 2013). Coral reefs have also increased in their estimated value, in terms of ES, from ~8000 to ~352,000 $/ha/y due to their recreational value and evidence that they function in storm and erosion protection (Costanza et al., 2014). The sustainability and protection of these ES and the associated biodiversity needs to be a priority in ocean governance to avoid the rise of mediocrity in coral reefs (Mumby, 2017).

Reef environments have been protected mainly through the establishment of marine protected areas (MPA) in coastal and oceanic habitats, with differing results based on the region (Mora and Sale, 2011; Gill et al., 2017) and the resilience of the coral reef (Mora et al., 2016). Despite satisfactory implementation of MPAs and management of local pressures, these ecosystems are susceptible to degradation because of the regional and global impacts of human pressures (Halpern et al., 2015; Altieri et al., 2017). The policy discussion on MPAs worldwide usually focuses on coastal tropical reefs, although extensive marine zones, including some reefs located in the offshore regions, such as seamounts and atolls, lack effective protective measures or environmental management (Edgar et al., 2014).

The management of offshore MPAs worldwide (including atolls and islands) is a challenge for the multiple stakeholders involved in ocean governance (Morais et al., 2015; Andrade and Soares, 2017). Little or no availability of freshwater and fisheries, susceptibility to erosion, the presence of endemic species, and vulnerability to climate change are complex factors that must be considered in the management of oceanic reefs (Woodroffe, 2008). Moreover, it is necessary to understand the management practices, and cumulative stressors that affect offshore MPAs in order to discuss the challenges faced and the role of science in improving ocean governance.

This study aimed to determine the main anthropogenic pressures and the effectiveness of management practices in marine protected areas (MPAs) located in the Tropical South Atlantic Ocean (Rocas Atoll and Fernando de Noronha Archipelago, Brazil). I also presented an overview of the environmental characteristics and effective management practices. Considering local, regional, and global human drivers (Oesterwind et al., 2016) at the only atoll in the South Atlantic (Rocas Atoll), the major anthropogenic pressures, such as marine pollution (i.e., microplastics), exotic species, range shifts of species, acidification, sea-level rise (SLR), and the effects of global warming, were reviewed. Finally, strategies for large scale marine spatial planning, as well as

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https://doi.org/10.1016/j.marpolbul.2018.04.008
Received 20 December 2017; Received in revised form 5 April 2018; Accepted 6 April 2018
Available online 22 April 2018

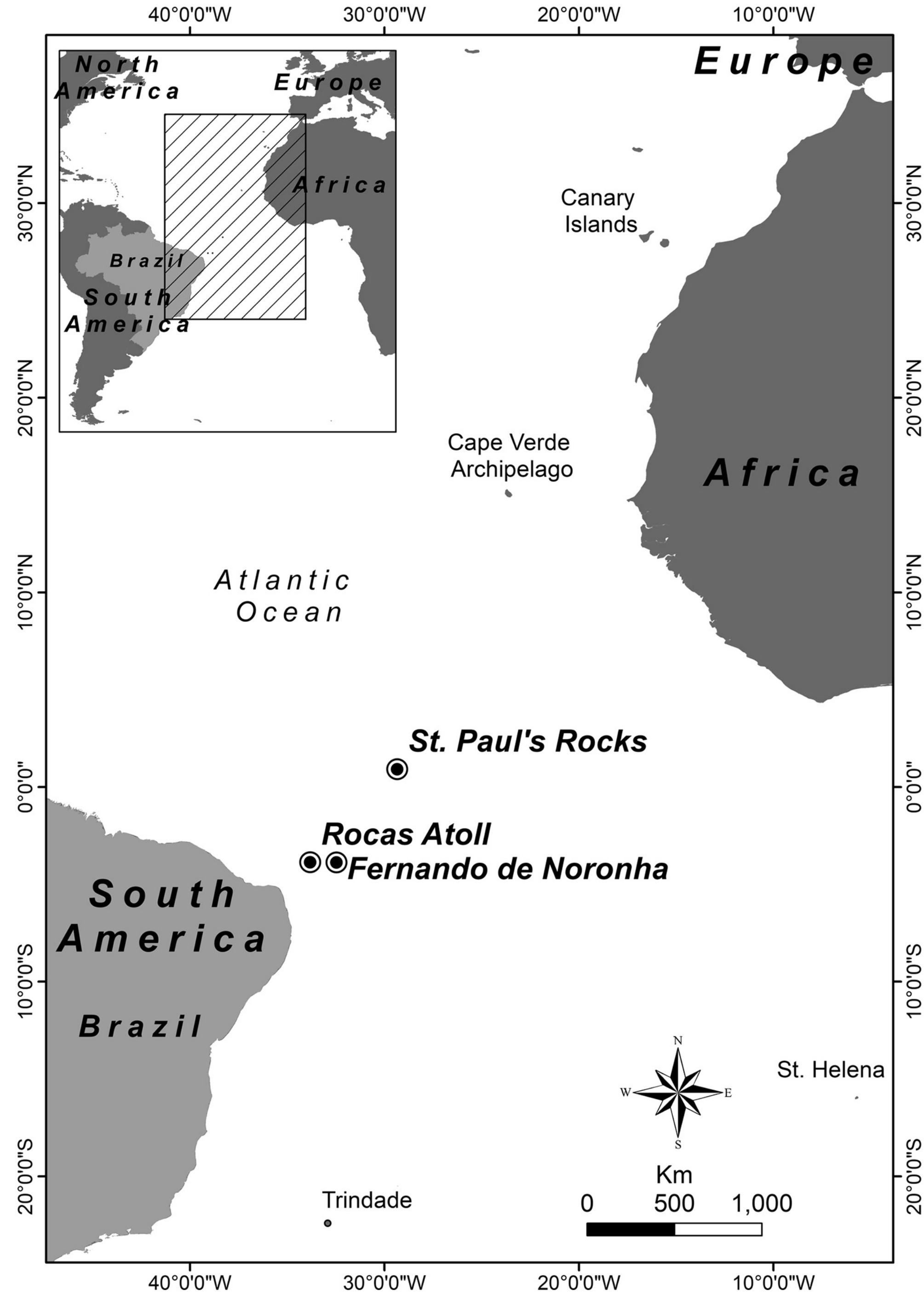

Fig. 1. Map of the Tropical South Atlantic islands (highlighted in bold).

proposals for an integrated management of MPAs (including coral reef islands and seamounts) by the articulation of a network in South Atlantic, which reduces regional human pressures and improves ocean governance were discussed.

2. Characteristics and management of offshore MPAs in the tropical South Atlantic

2.1. The insular environment

Oceanic islands in the tropical South Atlantic are important marine habitats where tropical reefs occur. These islands include the Fernando de Noronha Archipelago, Rocas Atoll (the only atoll in the South Atlantic), and the Saint Paul and Saint Peter Archipelago (Fig. 1). They vary in size, the largest being Fernando de Noronha, and distance from the mainland, the most remote being Saint Paul and Saint Peter Archipelago, and have distinct biodiversity and insular ecosystems. These environments are considered recent, as they are located in the tropical region of the youngest ocean (South Atlantic) on earth, and constitute one of most important biodiversity hotspots worldwide (Hachich et al., 2015; Barroso et al., 2016). They can provide ecological insights into the high biodiversity and resilience against climate change of oceanic islands (Leão et al., 2016; Soares et al., 2017).

One of most important oceanic islands in the South Atlantic, in terms of marine conservation, is Rocas Atoll. In recent geological history, approximately 425 atolls have been observed. Most of them are

Fig. 2. The presence of a lagoon (I), intertidal sand flat (II), sand cays: Farol Island (III-A), Cemitério Island (III-B), reef flat and tide pools (IV), and reef ridge (V and VI), characterize the geomorphology of Rocas Atoll. In the sandy deposit, the two sandy cays, Farol and Cemitério Island, are the only places that remain visible during high tide.

located in the Indo-Pacific Ocean and 27 are located in the Atlantic Ocean, primarily in the Caribbean Sea (Bryan, 1953). Rocas Atoll is the only atoll in the South Atlantic. This oceanic reef is located at the top of a chain of seamounts that are 267 km off the coast of Northeast Brazil and 4000 m deep. Rocas Atoll is an oceanic reef consisting of two small islands and a shallow lagoon (Fig. 2). It is one of the smallest atolls in the world (Gherardi and Bosence, 1999). It is approximately 150 km west of Fernando de Noronha Archipelago, with which it shares endemic species (Hachich et al., 2015; Barroso et al., 2016).

Despite its small size, UNESCO has considered Rocas Atoll and the Fernando de Noronha Archipelago, a natural world heritage site since 2001. These islands represent a significant portion of the island surface of the South Atlantic and their productive oceanic waters (Tchamabi et al., 2017) are important for the breeding, reproduction, and feeding of fishes, sharks, endangered turtles, and marine mammals (UNESCO, 2017). Moreover, the islands are home to the largest concentration of tropical seabirds in the Western Atlantic (UNESCO, 2017) and exhibit a high degree of endemism (Paiva et al., 2015; Hachich et al., 2015; Barroso et al., 2016). Moreover, total biomass of reef fishes was generally higher at these oceanic islands (Morais et al., 2017). However, Halpern et al. (2015) calculate the recent change over 5 years (2008–2013) in cumulative human impacts to marine ecosystems. The marine ecoregion of Rocas Atoll and Fernando de Noronha show increased human impact, driven mostly by fishing, shipping, and climate change pressures (ocean acidification, sea surface temperature, and sea-level rise).

This study use the only atoll from South Atlantic, Rocas atoll, as a case study because they can be considered as a "pristine reef" (Longo et al., 2015; Leão et al., 2016) and a model to discuss the effectiveness of site-specific management. At Rocas Atoll, local pressures have been managed using a site-specific approach along with an adequate marine policy based on the conditions of no-take MPAs and the highly effective management practices conducted in the last 25 years (1990–2015) (Soares et al., 2010; Brandão et al., 2017). However, high site-specific management may not be enough for conservation in the face of increasing threats by global environmental change. Indeed, a more holistic approach to management (including other South Atlantic islands) may be required in the face of growing regional and global pressures.

2.2. Management effectiveness

The biological reserve of Rocas Atoll was created in 1979 (Law 83.549, dated June 5, 1979) and encompasses a region of about 360 km^2 around the reef ring, formerly reaching depths of about 1000 m. This offshore MPA is the first Brazilian no-take MPA (strictly protected area) and the first reef system protected off the South Atlantic Ocean. As a no-take MPA, it is closed to public access and managed for research and the protection of insular species (Soares et al., 2010). It is located within 200 nmi of the Brazilian jurisdictional waters and is defined as an Exclusive Economic Zone (EEZ) in accordance with the United Nations Convention on the Law of the Sea. This MPA has a buffer zone that can be defined as the "surroundings of a conservation unit where human activities are subject to specific norms and restrictions, in order to minimize negative pressures on the protected area." The buffer zone is bounded by a rectangle (60 × 50 nmi) that covers the seamount where the atoll is located and two adjacent seamounts east of

the MPA (Soares et al., 2010).

Of all the important reef ecosystems in the Tropical South Atlantic (i.e., Abrolhos and Fernando de Noronha), Rocas Atoll showed the highest management effectiveness. The levels of effectiveness were ~47%, 68%, 59% and 81% in 1990, 2005, 2010, and 2015, respectively (Soares et al., 2010; Brandão et al., 2017), indicating an increase in value over time and satisfactory levels of management. Soares et al. (2010) and Brandão et al. (2017) analyzed this offshore MPA using the RAPPAM (Rapid Assessment and Prioritization of Protected Area Management) method and detected decreases in local pressures and threats over the duration of the analysis. The RAPPAM method is one of the most accepted methods for assessing management effectiveness as it allows for a global analysis, identifying strengths and weaknesses, and analyzing pressures and threats (Leverington et al., 2010).

The adequate demarcation of MPA, existence of management plan, environmental zoning, financial and human resources, effective surveillance of illegal uses, good infrastructure (scientific station and boats), and high biological importance (endemism and richness of species) are positive aspects of the management effectiveness of the Rocas Atoll (Soares et al., 2010; Brandão et al., 2017).

Two recent global studies on MPAs suggested that social and ecological characteristics correlated with effective management. Edgar et al. (2014) suggested that the conservation benefits of MPAs increase with the accumulation of five key features: it must be no-take, well enforced, old (> 10 years), large (> 100 km^2), and isolated by deep waters or sand. Gill et al. (2017), using a global database of management in MPAs, found that effective biodiversity conservation was heavily dependent on available capacity (i.e., staff and budget capacity). These authors also found that clearly defined boundaries and appropriate regulations correlated with better ecological outcomes. The offshore MPA that protects Rocas Atoll has all these characteristics (Soares et al., 2010; Brandão et al., 2017).

3. Regional and global pressures: A challenge for ocean governance

3.1. Regional pressures

Regional (manageable) and global (unmanageable by local efforts) pressures challenge the effective management of the offshore MPA Rocas Atoll (Fig. 3). The main regional pressures are: 1) Increases in fishing pressures in the buffer zone and inside MPA Rocas Atoll within the next decades; 2) introduction of exotic species; 3) range-shifts of species, induced by direct human pressures and climate change; and 4) marine debris and microplastics.

The oceanic waters around the islands of Rocas Atoll and Fernando de Noronha are quite productive due to the "island mass effect" (Tchamabi et al., 2017), which allows them to sustain large populations of fishery resources (Morais et al., 2017). Moreover, unlike other oceanic areas, such as the Archipelago of Saint Paul's Rocks, where fishing pressures promoted the local extinction of reef sharks (Luiz and Edwards, 2011), the MPA of Rocas Atoll is a no-take area. Efficient surveillance and access difficulties have reduced fishing pressures and helped improve the conservation of fishery resources in this offshore MPA. Despite controls put in place to reduce local human pressures on fisheries inside the Rocas Atoll, it is necessary to fulfill national and international agreements and establish appropriate management practices for regional fisheries on South Atlantic islands using large scale marine spatial planning. These measures could efficiently minimize the increases in fishing pressures in the buffer zone and inside MPA Rocas Atoll within the next decades.

Exotic species have negative effects on biodiversity and ecological processes, especially on islands, as invasive species can usurp native species and are therefore very threatening to marine biodiversity. Due to effective surveillance and the absence of urban sites in Rocas Atoll, the impact of invasive species on this MPA is low. Currently there are records of terrestrial invertebrates (scorpions and rats) in sand cays (Soares et al., 2010) and some non-indigenous marine species (Paiva et al., 2015), that have no significant impact on the conservation of native benthic species. However, the dispersion of invasive species along the Southwestern Atlantic coast (Campos et al., 2017; Castro et al., 2017) and the presence of shipping traffic and touristic boats (Lopes et al., 2017) in Fernando de Noronha Archipelago increase the environmental risk of bioinvasion in this offshore MPA.

The sun corals *Tubastraea coccinea* and *T. tagusensis* were the first invasive scleractinian species to be introduced to the South Atlantic and negatively affect coral reefs (Creed et al., 2017). They alter the native benthic assemblages (via competition with native corals and zoanthids) and ecological interactions between species. The recent record of *T. tagusensis* in the equatorial margin of the South Atlantic coast (Soares et al., 2016) and the geographical proximity of such coastal regions to the islands (~300 km) represent an increased environmental risk of bioinvasion. Although these invasive species cannot be dispersed over long distances or through ballast water (Creed et al., 2017), these corals can reach the oceanic islands attached to oil and gas platforms, ships or monobuoys that operate in this region (Soares et al., 2016). Thus, environmental monitoring is necessary to reduce such risk to conservation in these offshore MPAs.

Range shifts of species (induced by climate change and direct human drivers, such as ships) (Madin et al., 2012) and the dispersion of invasive corals (*Tubastraea* spp.) along the South Atlantic coast (Creed et al., 2017) will remain an environmental threat over several decades. Recently, Sissini et al. (2014) recorded the presence of the algae *Halimeda opuntia* inside the MPA Rocas Atoll. In the 40 years of environmental monitoring of this oceanic reef, no scientist had observed the presence of these dominant algae before 2012. These algae are a very important and abundant component of benthic ecosystems worldwide. Its range shift to the only atoll from the South Atlantic was probably facilitated by biofouling on ship hulls or floating debris from the continent (or Fernando de Noronha Archipelago) (Sissini et al., 2014). The recent introduction of *Halimeda* may potentially alter the ecosystem functioning considering its high growth rates and the fact that this species is considered an "eco-engineering" organism that modifies the sea floor and associated biodiversity. In fact, *H. opuntia* is associated with dominance shifts from scleractinian corals to algae in the Caribbean Sea (Hughes et al., 2017). In marine ecosystems, range shifts, induced by local, regional, and global pressures, have been observed in a wide diversity of reef species, and are predicted to become more frequent as environmental conditions change (Madin et al., 2012). These results suggest that climate change scenarios can modify even the ecology of pristine ecosystems inside MPAs by causing species to shift their ranges.

Another regional pressure that occurs in Rocas Atoll is the presence of marine debris. Despite the absence of significant human activity (i.e., tourism, urban activities, and fisheries), Soares et al. (2011) found different types of marine debris (plastic, metal, cardboard, glass, nylon etc.,) that had been used for food, cleaning, and personal hygiene and were related to fisheries ("ghost nets"). Most items found in this atoll were from a foreign oceanic source (i.e., Argentina, Europe, and Asia), delivered by ships or discharged from the closer Fernando de Noronha Archipelago and transported by ocean currents. The marine debris generated by residents and visitors to the Fernando de Noronha Archipelago could have been carried by the South Equatorial Current (SEC) to Rocas Atoll, introducing invasive species as well as threatening the life of fishes, birds, turtles, and marine mammals by entrapment, ingestion of solid wastes, or contamination by microplastics. Moreover, plastic debris stresses reef-building species through light deprivation, anoxia, and toxin release, giving pathogens a foothold for invasion (Lamb et al., 2018).

Another regional pressure detected (Ivar do Sul et al., 2009, 2014) was the presence of pellets and microplastics in the tropical Atlantic Ocean (i.e., Fernando de Noronha Archipelago). Microplastics have

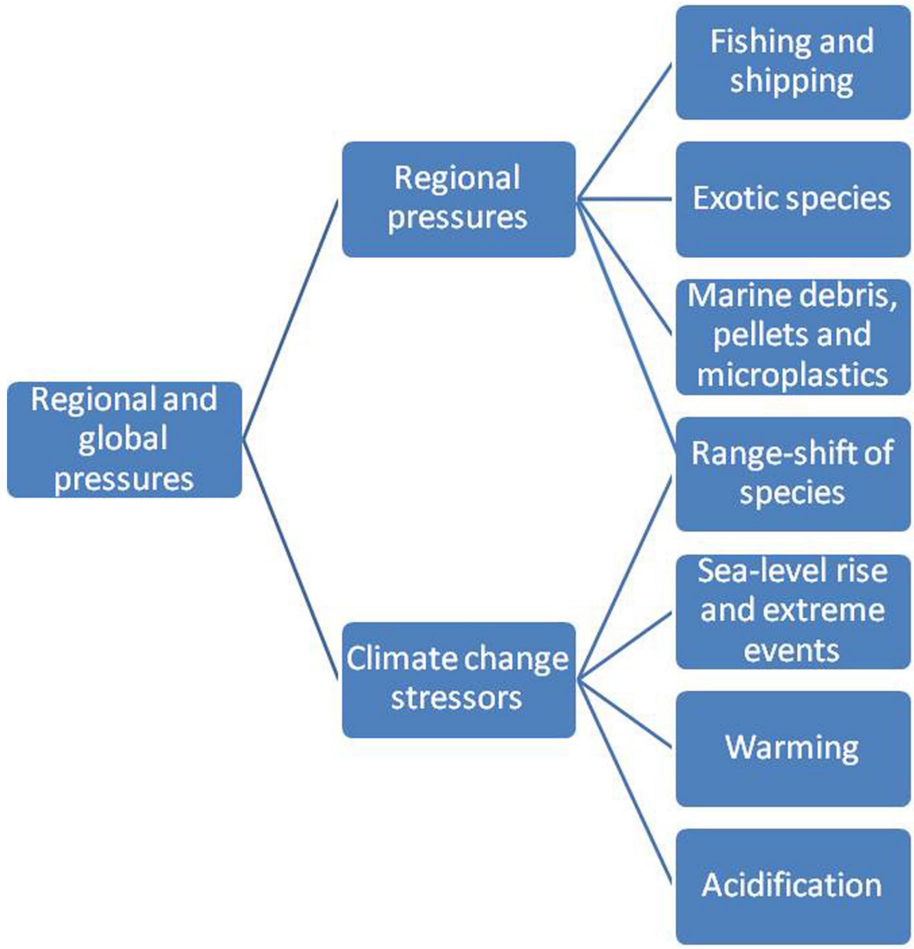

Fig. 3. Regional and global anthropogenic pressures on Rocas Atoll, South Atlantic.

piqued the interest of scientists and governments because they concentrate persistent organic pollutants (POPs), thereby representing a potential threat to important marine species and ecosystem processes (Derraik, 2002; Andrady, 2011). These regional pressures (marine debris, abandoned fishing gears, and microplastics) reinforce the idea that the establishment of large scale marine spatial planning is needed to reduce human drivers such as shipping lines, tourism, and fisheries.

3.2. Global pressures

There are three main effects of climate change on offshore MPAs worldwide: warming, SLR, and ocean acidification (OA) (Fig. 3), and all these anthropogenic pressures act together (Hoegh-Guldberg et al., 2007, 2017). Little is known about the cumulative impacts of these global anthropogenic stressors, as well as the resistance and resilience of offshore MPAs in South Atlantic with respect to climate change stressors. Although a fast rising sea level is predicted to destabilize reef islands, global warming and acidification are considered major threats to reef growth, which primarily affect the persistence of these environments (Duvat and Pillet, 2017; Hughes et al., 2017) in Tropical South Atlantic.

3.2.1. Sea surface anomalies

The increase in recent research on coral bleaching and sea surface anomalies in the SW Atlantic has been concentrated on the eastern coast of Brazil and oceanic islands (Fernando de Noronha and Rocas Atoll). Coral bleaching associated with the first semester (summer) is a phenomenon that has been observed in the South Atlantic, probably induced by El-Nino/Southern Oscillation (ENSO) events (Ferreira et al., 2013; Leão et al., 2016). These events are related to anomalies in sea surface temperature (SST), including several weeks of above average temperatures, high temperatures on the sea surface, and positive hotspot values. It is assumed that there is a relationship between coral bleaching, irradiation, and SST in the South Atlantic reefs (Leão et al., 2016).

Despite increased bleaching rates and coral diseases, the mass mortality of coral reefs had not been detected until now. These results suggest the resilience of reef-building corals against climate change stressors such as SST anomalies (Leão et al., 2016). Further investigation is necessary to calculate the resilience metrics (Mumby and Anthony, 2015) of this atoll considering its unique seascape mainly built by coralline algae and a few resilient scleractinian corals. In contrast to the atolls in the Indo-Pacific and Caribbean waters, which are mainly inhabited by hermatypic corals, the reef framework of Rocas Atoll is largely composed of crustose coralline algae, foraminiferans, and vermetid mollusks (Gherardi and Bosence, 1999, 2005) creating a unique sea- and landscape worldwide.

The past few years (2010, 2015, and 2016) were marked by anomalous high SST that led to a global bleaching event throughout the tropical coral reefs (Heron et al., 2016). In 2015–2016, record high temperatures triggered a pan-tropical episode of coral bleaching, the third global-scale event since mass bleaching was first documented in the 1980s. The challenge worldwide is to steer reefs through this period of continued warming, a fundamentally different mindset to the traditional focus of maintaining the status quo of tropical reefs. Hughes et al. (2017) showed that even reefs with low anthropogenic impacts (pristine and protected) are susceptible to much warmer waters, as the recent El Niño 2015/16 event showed. In the study site, Magris et al.

(2015) projected for the Rocas Atoll a severe thermal stress in the next decades. These disturbances (Degree heating weeks) are predicted to occur at a rate approaching six per decade (Hughes et al., 2018).

In Rocas Atoll, the main reef-building corals are "thermally-resistant" e.g., *Siderastrea* spp., *Porites* spp., *Montastraea cavernosa*, and "thermally-tolerant" *Favia gravida*. Ferreira et al. (2013) recorded anomalous temperatures in 2009 and 2010, which caused extensive coral bleaching. In Rocas Atoll and Fernando de Noronha Archipelago, SST was 1.67 °C above average in the reef environments. The results of Ferreira et al. (2013) indicated that the percentage of bleached corals that persisted after the subsidence of thermal stress increased during ENSO (2010). Moreover, the prevalence of diseases (black-band-like, white plague-like disease, and dark-spot-like diseases) increased in 2010 mainly in reef-building coral, *Siderastrea* spp., after two periods of thermal stress, which indicate the susceptibility of the only atoll in the South Atlantic to ENSO events and their potential detrimental effects on this pristine reef. Similarly, Pinheiro et al. (2017) predicted detrimental effects, despite some degree of resilience. These researchers analyzed the *S. stellata* population in Rocas Atoll and found a high potential for maintenance and recovery due to the early growth of primary polyps and high growth rate of adult colonies. They also reported impacts on coral recruitment, probably because of SST anomalies due to ENSO (2010).

The MPA of Rocas Atoll is a natural laboratory because it can be used as a model for understanding the range in natural variability and projected climate change effects (e.g., SLR and increased temperatures) on atolls. This MPA is in pristine condition with very low local anthropogenic pressures, minimal SST seasonal variability (26–29 °C), and large inter-annual variability ranging from 24 to 30 °C over the last 30 years (Pereira et al., 2017). Rocas Atoll can be used to reconstruct climate oscillations over time using geochemical information from massive corals. Pereira et al. (2015) analyzed colonies of coral (*Porites astreoides*) affected by the 2009/2010 El-Niño event – a period of widespread coral bleaching – and suggested that corals from Rocas Atoll could be used for monitoring inter-annual climate variability in the Tropical South Atlantic Ocean.

3.2.2. Sea-level rise and ocean acidification

Recent studies (Pereira et al., 2010; Costa et al., 2017) suggested some degree of resilience against SLR and extreme events (swell waves and currents) in the reef islands in this offshore MPA. These islands are located on the leeward side of the atoll and exhibit higher morphological changes in response to the northern swell. Pereira et al. (2010) conducted a historical mapping of the atoll and found that the main sand cay (Farol island) had a growth of nearly 47,000 m^2 with a substantial accretion on a decadal time scale, which may be related to the high level of carbonate particle production in the reef complex and the increase in local hydrodynamics. Costa et al. (2017) argued that Cemitério Island remained stable for the same period, anchored by exposed consolidated sediments on both shores. They observed no significant net erosion on a daily and seasonal time scale, as eroded parts were compensated for by accretion on adjacent parts. The changes in sediment dynamics were characterized by ocean shoreline erosion and lagoon shoreline progradation, representing net lagoonward migration.

Both studies (Pereira et al., 2010; Costa et al., 2017) indicated the resilience of sand cays and their potential adjustment to environmental changes. This shows that, under predicted SLR scenarios, areas prone to sediment accumulation may become less stable, although this does not denote the erosion of these islands. Nevertheless, Pereira et al. (2010) and Costa et al. (2017) suggested the need for further studies to analyze the future trend of erosion based on SLR and extreme events such as swell waves and tides. As the sandy cays are not much higher than sea level (Farol Island, 3.6 m; Cemetery Island, 2.8 m) (Gherardi and Bosence, 2005), small eustatic oscillations are capable of causing major changes to the geomorphology of these islands. This environmental feature is fundamental for the long-term environmental planning of the MPA.

During the 20th century, an increase in atmospheric carbon dioxide (CO_2atm) depleted seawater carbonate concentrations and enhanced acidity. A similar increase in CO_2atm is expected in the 21st century, accelerating the process of OA in reefs worldwide (Hoegh-Guldberg et al., 2017; Hughes et al., 2017). Honisch et al. (2012) evaluated the geological records of OA and concluded that we are experiencing an unprecedented increase in CO_{2atm} release that will disrupt the balance of ocean carbonate chemistry. This phenomenon will compromise carbonate accretion in key reef species (Hughes et al., 2017) and benefit mat-forming algae (Connell et al., 2013) in all reef environments, including the oceanic atolls. Eyre et al. (2018) report that some tropical reefs are already experiencing net sediment dissolution. Moreover, the rates of loss will increase as OA intensifies. OA is the least studied global change stressor in the Tropical SW Atlantic (Kerr et al., 2016) and represents an environmental risk to the conservation of the only atoll in the South Atlantic.

The reef framework of Rocas Atoll is largely built by crustose coralline algae (CCA) (e.g., *Porolithon pachydermum*), foraminiferans, and vermetid mollusks (e.g., *Dendropoma irregulare*) (Gherardi and Bosence, 1999, 2005). Kuffner et al. (2008) conducted an experiment exploring the effects of acidification in CCA and found that recruitment rate and growth were severely inhibited in elevated carbon dioxide mesocosms. The authors also found that the coralline algae, *Porolithon onkodes* (same genus of an important bioconstructor of Rocas Atoll), is sensitive to OA under warm conditions. Warmer temperatures and acidity increase the mortality and skeletal dissolution of this species (Diaz-Pulido et al., 2011). Long-term environmental monitoring of the effects of acidification and multiple human pressures (i.e., SST anomalies) and their negatives impacts on marine calcifiers is recommended.

4. Recommendations and future directions

4.1. A network of MPAs in the South Atlantic Ocean

The management effectiveness of the MPA Rocas Atoll, mainly in the control of local anthropogenic pressures, has been considered satisfactory. However, increased regional and global pressures require the adoption of more integrated management using large scale marine spatial planning. One important recommendation is the adoption of a network (also called mosaic) of MPAs in the South Atlantic to improve the management of their ocean basin.

Researchers (Hachich et al., 2015; Barroso et al., 2016) showed that there is a clear connection between the Fernando de Noronha and Rocas Atoll islands in terms of ecological processes, based on their shared endemic species. This study and these results indicate that these processes and regional anthropogenic pressures are not currently taken into account in the design of conservation programs and need to be considered to improve conservation. Some required measures include: 1) the establishment of the first network of oceanic protected areas in the South Atlantic Ocean, and 2) expansion of the marine protected areas via an ecological corridor between the two islands.

The proposed network can be defined as a collection of individual MPAs (Costello et al., 2009) operating cooperatively on a regional spatial scale with two protection levels (restricted protection and direct use) that are designed to meet objectives that a single biological reserve (i.e., Rocas Atoll) cannot achieve (see an interactive map in online version of manuscript). This network is necessary to reduce regional human pressures (i.e., microplastics and invasive species), conserve insular biodiversity, including shared endemic species, and increase the supply of resources (including financial resources) available for management.

The network can include the Biological Reserve of Rocas Atoll (described in this study) and two MPAs of Fernando de Noronha Archipelago (Marine National Park and Environmental Protected Area) of different sizes. The Fernando de Noronha Archipelago MPA is

divided into two distinct management categories: 70% of its area is a no-take zone (controlled tourism and recreational diving activities are allowed) and 30% is a sustainable use zone (residences, tourism and fisheries are permitted). Following the Brazilian protected area system, the no-take zone is called "Marine National Park", while the remaining is called "Environmental Protection Area" (Lopes et al., 2017). These MPAs are located in critical habitats (Fernando de Noronha ridge), and are interconnected by marine larvae and plant propagules (Ross et al., 2017). The Rocas Atoll and Fernando de Noronha are influenced by the westward flow of the central South Equatorial Current (Tchamabi et al., 2017).

This MPA Network can be established to conserve biodiversity and reduce regional human pressures and protect the connection between these two insular environments as larvae migration between the Fernando de Noronha MPAs (more impacted area) and Rocas Atoll MPA (pristine environment). This MPA mosaic can provide a unified framework of environmental management, conservation, research, and fishery management (Geange et al., 2017).

On the basis of our findings and the ecological flow between Rocas Atoll and Fernando de Noronha Archipelago (Hachich et al., 2015; Barroso et al., 2016), I also suggested the delimitation of the submarine chain that interconnects these islands as a new MPA. The mountain beneath Fernando de Noronha extends 4000 m below sea level and is a small part of an alignment of submerged east-west volcanic highs along the fracture zone, which form the Fernando de Noronha Chain within Rocas Atoll (Gherardi and Bosence, 2005). This area had not been analyzed in biological and geological terms until now and it should be the subject of an extensive environmental analysis and management plan.

A recent study (Amado Filho et al., 2016) described the mesophotic ecosystems (MEs) in Rocas Atoll; in the study, the rhodolith beds were the main ecosystem, and were composed mainly of crustose coralline algae, and contained different reef structures, such as the formation of carbonate reefs by the coalescence of rhodoliths. The Fernando de Noronha Archipelago is also surrounded by poorly studied MEs (rhodolith beds). MEs are included in these MPAs; however, more studies are necessary to increase the number of MEs and deep-sea ecosystems that are protected. Mapping of the sea floor around the offshore MPA is necessary to understand the distribution and diversity of marine biodiversity, including oceanic ecosystems that can be covered by a network of MPAs. This information is fundamental to promote specific strategies for the protection of benthic marine ecosystems and expand MPAs, including the poorly known MEs and deep-sea benthic communities near the South Atlantic islands.

This newly offshore marine protected area is in accordance with the specifications of COP-10 and can be part of the South Atlantic MPA network, a conservation policy already observed in other countries and oceans. As part of the 2011 Convention on Biological Diversity (CBD) Aichi Targets, 193 countries agreed to effectively manage 10% of the coastal and marine areas within MPAs by 2020. Gill et al. (2017) argued that the continued expansion (currently 4.1%) of MPAs needs an adequate human and financial investment to reach conservation goals.

4.2. Cumulative pressures and resilience metrics to inform management

The cumulative/synergistic pressures (i.e., global warming, range shifts of species, and OA) are the major challenges affecting the management of coral reefs (Aswani et al., 2015). Reducing local stressors could mitigate the impacts of global stressors and improve the resilience of high-diversity reefs (Ferrigno et al., 2016). Resilience analyses assess the importance of local- or regional-scale management decisions under various degrees of global environmental change. Research that evaluate the resilience of reefs in the face of global environmental change have been based on environments dominated by scleractinian corals (Mumby and Anthony, 2015), which are common in Caribbean and Indo-Pacific.

The current metrics for calculating reef resilience is based on the high coral coverage and environmental characteristics (Maynard et al., 2015) common to other oceans. However, the only South Atlantic atoll is a healthy system dominated by coralline algae and vermetids, and a low richness of coral species (Gherardi and Bosence, 1999, 2005; Longo et al., 2015). These coral species are known for their resistance to adverse environmental conditions, such as SST oscillations and high irradiance (Leão et al., 2016). Thus, more scientific studies to establish adequate metrics and quantify the resilience of tropical reefs in the South Atlantic Ocean are necessary.

Current literature suggests that preserved tropical environments would have better resilience against global environmental changes (i.e., elevation of SST) (Aswani et al., 2015) and invasive species (i.e., theory of biotic resistance). The low pressure of human pressures in Rocas Atoll has led to a pristine environment with a high degree of preservation. A high degree of resilience in relation to the global and regional anthropogenic stressors is possible in such a pristine Atoll. However, the lack of long-term ecological studies and the distinctiveness of this oceanic environment require caution in terms of predicting its resilience, emphasizing the need to establish quantitative metrics to assess its resilience and ecological connectivity (Standish et al., 2014). The highly effective management practices adopted in the last 25 years should continue, as they will contribute to the recovery and resilience of the ecosystems against extreme events and inter-annual variability of climate and human disturbances in the Anthropocene.

Data on resilience can be used to inform management practices in the MPAs. A continuous improvement of management effectiveness is necessary to sustain the protection of the offshore MPAs in South Atlantic. Thus, the effective management in the Rocas Atoll can be considered an exception (and a good model) in the Brazilian Conservation System and is probably due to the intense environmental monitoring, scientific research, planning, and control of local human pressures in the last two decades. However, in terms of global environmental change, rectifying these measures is an urgent priority to establish the effective management of MPAs of South Atlantic islands mainly to address the resilience, ecological connectivity, and regional pressures between Fernando de Noronha Archipelago and Rocas Atoll.

5. Conclusions

This study argued (considering the scientific evidence) that high site-specific management might not be sufficient for conservation in the face of growing threats of global environmental change. A more holistic approach in environmental management that considers the connections between island biodiversity and human impacts is necessary to improve ocean governance. The conservation of the offshore MPAs involves: 1) improving long-term environmental planning and monitoring while taking climate change-related stressors and regional human pressures into consideration, and 2) implementing large scale marine spatial planning with the South Atlantic islands and seamounts.

Acknowledgments

I would like to thank valuable comments for the manuscript from Dra. Hortencia Barroso, Dra.Tallita Tavares and Dr. Gleidson Gastão. I thank anonymous referees for their constructive comments on a previous version of this paper. I would like to thank CNPq (Process 233808/2014-0 and Process 307061/2017-5) and INCT AmbTropic (CNPq/CAPES).

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:https://doi.org/10.1016/j.marpolbul.2018.04.008. These data include the Google map of the most important areas described in this article.

References

Altieri, A.H., Harrison, S.B., Seemann, J., Collin, R., Diaz, R.J., Knowlton, N., 2017. Tropical dead zones and mass mortalities on coral reefs. PNAS 114 (14), 3660–3665. http://dx.doi.org/10.1073/pnas.1621517114.

Amado Filho, G.M., Moura, R.L., Bastos, A.C., Francini-Filho, R.B., Pereira Filho, G.H., Bahia, R.G., Moraes, F.C., Motta, F.S., 2016. Mesophotic ecosystems of the unique South Atlantic atoll are composed by rhodolith beds and scattered consolidated reefs. Mar. Biodivers. http://dx.doi.org/10.1007/s12526-015-0441-6.

Andrade, A.B., Soares, M.O., 2017. Offshore marine protected areas: divergent perceptions of divers and artisanal fishers. Mar. Policy 76, 107–113. http://dx.doi.org/10.1016/j.marpol.2016.11.016.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62 (8), 1596–1605. http://dx.doi.org/10.1016/j.marpolbul.2011.05.030.

Aswani, S., Mumby, P.J., Baker, A.C., Christie, P., McCook, L.J., Steneck, R.S., Richmond, R.H., 2015. Scientific frontiers in the management of coral reefs. Front. Mar. Sci. 2, 50. http://dx.doi.org/10.3389/fmars.2015.00050.

Barroso, C.X., Lotufo, T.M.C., Bezerra, L.E.A., Matthews-cascon, H., 2016. A biogeographic approach to the insular marine prosobranch gastropods from the southwestern Atlantic Ocean. J. Molluscan Stud. 82, 558–563. http://dx.doi.org/10.1093/mollus/eyw015.

Brandão, C.S., Malta, A., Schiavetti, A., 2017. Temporal assessment of the management effectiveness of reef environments: the role of marine protected areas in Brazil. Ocean Coast. Manag. 142, 111–121. http://dx.doi.org/10.1016/j.ocecoaman.2017.03.015.

Bryan, E.H., 1953. Check list of atolls. Atoll Res. Bull. 19, 1–38.

Campos, C.C., Garcia, T.M., Neumann-Leitão, S., Soares, M.O., 2017. Ecological indicators and functional groups of copepod assemblages. Ecol. Indic. 83, 416–426. http://dx.doi.org/10.1016/j.ecolind.2017.08.018.

Castro, M.C.T., Fileman, T.W., Hall-Spencer, J.M., 2017. Invasive species in the northeastern and southwestern Atlantic Ocean: a review. Mar. Pollut. Bull. 116 (1–2), 41–47. http://dx.doi.org/10.1016/j.marpolbul.2016.12.048.

Connell, S.D., Kroeker, K.J., Fabricius, K.E., Kline, D.I., Russell, B.D., 2013. The other ocean acidification problem: CO_2 as a resource among competitors for ecosystem dominance. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 368 (1627). http://dx.doi.org/10.1098/rstb.2012.0442.

Costa, M.B., Macedo, E.C., Valle-Levinson, A., Siegle, E., 2017. Wave and tidal-flushing in a near-equatorial mesotidal atoll. Coral Reefs 36 (1), 277–291. http://dx.doi.org/10.1007/s00338-016-1525-x.

Costanza, R., de Groot, R., Sutton, P., Ploeg, S.V.D., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158. http://dx.doi.org/10.1016/j.gloenvcha.2014.04.002.

Costello, C., Rassweiler, A., Siegel, D., De Leo, G., Micheli, F., Rosenberg, A., 2009. The value of spatial information in MPA network design. PNAS 107 (43), 18294–18299. http://dx.doi.org/10.1073/pnas.0908057107.

Creed, J.C., Fenner, D., Sammarco, P., Cairns, S., Capel, K., Junqueira, A.O.R., Cruz, I., Miranda, R.J., Carlos-Júnior, L., Mantellato, M.C., Oigman-Pszczol, S., 2017. The invasion of the azooxanthellate coral Tubastraea (Scleractinia: Dendrophylliidae) throughout the world: history, pathways and vectors. Biol. Invasions 19 (1), 283–305. http://dx.doi.org/10.1007/s10530-016-1279-y.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44 (9), 842–852. http://dx.doi.org/10.1016/S0025-326X(02)00220-5.

Diaz-Pulido, G., Anthony, K.R.N., Kline, D.I., Dove, S., Hoegh-Guldberg, O., 2011. Interactions between ocean acidification and warming on the mortality and dissolution of coralline algae. J. Phycol. 48 (1), 32–39. http://dx.doi.org/10.1111/j.1529-8817.2011.01084.x.

Duvat, V.K.E., Pillet, V., 2017. Shoreline changes in reef islands of the Central Pacific: Takapoto atoll, northern Tuamotu, French Polynesia. Geomorphology 282, 96–118. http://dx.doi.org/10.1016/j.geomorph.2017.01.002.

Edgar, G.J., Stuart-Smith, R.D., Willis, T.J., Kininmonth, S., Baker, S.C., Banks, S., Barrett, N.S., Becerro, M.A., Bernard, A.T., Berkhout, J., Buxton, C.D., 2014. Global conservation outcomes depend on marine protected areas with five key features. Nature 506, 216–220. http://dx.doi.org/10.1038/nature13022.

Elliff, C.I., Kikuchi, R.K.P., 2017. Ecosystem services provided by coral reefs in a southwestern Atlantic archipelago. Ocean Coast. Manag. 136, 49–55. http://dx.doi.org/10.1016/j.ocecoaman.2016.11.021.

Eyre, B.D., Cyronak, T., Drupp, P., De Carlo, E.H., Sachs, J.P., Andersson, A.J., 2018. Coral reefs will transition to net dissolving before end of century. Science 359, 908–911. http://dx.doi.org/10.1126/science.aao1118.

Ferreira, B.P., Costa, M.B.S.F., Coxey, M.S., Gaspar, A.L.B., Veleda, D., Araujo, M., 2013. The effects of sea surface temperature anomalies on oceanic coral reef systems in the southwestern tropical Atlantic. Coral Reefs 32, 441–454. http://dx.doi.org/10.1007/s00338-012-0992-y.

Ferrigno, F., Bianchi, C.N., Lasagna, R., Morri, C., Russo, G.F., Sandulli, R., 2016. Corals in high diversity reefs resist human impact. Ecol. Indic. 70, 106–113. http://dx.doi.org/10.1016/j.ecolind.2016.05.050.

Geange, S.W., Leathwick, J., Linwood, M., Curtis, H., Duffy, C., Funnell, G., Cooper, S., 2017. Integrating conservation and economic objectives in MPA network planning: a case study from New Zealand. Biol. Conserv. 210, 136–144. http://dx.doi.org/10.1016/j.biocon.2017.04.011.

Gherardi, D.F.M., Bosence, D.W.J., 1999. Modeling of the ecological succession of encrusting organisms in recent coralline-algal frameworks from atoll das Rocas, Brazil. PALAIOS 14 (2), 145–158.

Gherardi, D.F.M., Bosence, D.W.J., 2005. Late Holocene reef growth and relative sea-level changes in Atol das Rocas, equatorial South Atlantic. Coral Reefs 24, 264–272. http://dx.doi.org/10.1007/s00338-005-0475-5.

Gill, D.A., et al., 2017. Capacity shortfalls hinder the performance of marine protected areas globally. Nature 543, 665–669. http://dx.doi.org/10.1038/nature21708.

Hachich, N.F., Bonsall, M.B., Arraut, E.M., Barneche, D.R., Lewinsohn, T.M., Floeter, S.R., 2015. Island biogeography: patterns of marine shallow-water organisms in the Atlantic Ocean. J. Biogeogr. 42, 1871–1882. http://dx.doi.org/10.1111/jbi.12560.

Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J.S., Rockwood, R.C., Selig, E.R., Selkoe, K.A., Walbridge, S., 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. Nat. Commun. 6, 7615. http://dx.doi.org/10.1038/ncomms8615.

Heron, S.F., Maynard, J.A., van Hooidonk, R., Eakin, C.M., 2016. Warming trends and bleaching stress of the World's coral reefs 1985–2012. Sci. Rep. 6, 38402. http://dx.doi.org/10.1038/srep38402.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E., 2007. Coral reefs under rapid climate change and ocean acidification. Science 318, 1737–1742. http://dx.doi.org/10.1126/science.1152509.

Hoegh-Guldberg, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., 2017. Global warming and recurrent mass bleaching of corals. Nature 543, 373–377. http://dx.doi.org/10.1038/nature21707.

Honisch, B., Ridgwell, A., Schmidt, D.N., Thomas, E., Gibbs, S.J., Sluijs, A., Zeebe, R., Kump, L., Martindale, R.C., Greene, S.E., Kiessling, W., 2012. The geological record of ocean acidification. Science 335 (6072), 1058–1063. http://dx.doi.org/10.1126/science.1208277.

Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson, J.B.C., Kleypas, J., Leemput, I.A.V., Lough, J.M., Morrison, T.H., Palumbi, S.R., Nes, E.V., Scheffer, M., 2017. Coral reefs in the Anthropocene. Nature 546, 82–90. http://dx.doi.org/10.1038/nature22901.

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.P.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., McCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G., Wilson, S.K., 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359 (6371), 80–83. http://dx.doi.org/10.1126/science.aan8048.

Ivar do Sul, J.A., Spengler, A., Costa, M.F., 2009. Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (equatorial western Atlantic). Mar. Pollut. Bull. 58, 1229–1244. http://dx.doi.org/10.1016/j.marpolbul.2009.05.004.

Ivar do Sul, J.A., Costa, M.F., Fillmann, G., 2014. Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean. Water Air Soil Pollut. 225, 1–13. http://dx.doi.org/10.1007/s11270-014-2004-z.

Kerr, R., Cunha, L.C., Kikuchi, R.K.P., Horta, P., Ito, R.G., Muller, M.N., Orselli, I.B.M., Lencina-Avila, J.M., De Orte, M.R., Sordo, L., Pinheiro, B., Bonou, F.K., Schubert, N., Bergstrom, E., Copertino, M.S., 2016. The western South Atlantic Ocean in a high-CO2 world: current measurement capabilities and perspectives. Environ. Manag. 57, 740–752. http://dx.doi.org/10.1007/s00267-015-0630-x.

Kuffner, I.B., Andersson, A.J., Jokiel, P.L., Rodgers, K.S., Mackensie, F.T., 2008. Decreased abundance of crustose coralline algae due to ocean acidification. Nat. Geosci. 1, 114–117. http://dx.doi.org/10.1038/ngeo100.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460–462. http://dx.doi.org/10.1126/science.aar3320.

Leão, Z.M.A.N., Kikuchi, R.K.P., Ferreira, B.P., Neves, E.G., Sovieroski, H.H., Oliveira, M.D., Maida, M., Correia, M.D., Johnsson, R., 2016. Brazilian coral reefs in a period of global change: a synthesis. Braz. J. Oceanogr. 64 (2), 97–116. http://dx.doi.org/10.1590/S1679-875920160916064sp2.

Leverington, F., Costa, K.L., Courrau, J., Pavese, H., Nolte, C., Marr, M., Coad, L., Burgess, N., Bomhard, B., Hockings, M., 2010. Management Effectiveness Evaluation in Protected Areas –a Global Study, Second edition. The University of Queensland, Brisbane, Australia (87p).

Longo, G.O., Morais, R.A., Martins, C.D.L., Mendes, T.C., Aued, A.W., Cândido, D.V., de Oliveira, J.C., Nunes, L.T., Fontoura, L., Sissini, M.N., Teschima, M.M., 2015. Between-habitat variation of benthic cover, reef fish assemblage and feeding pressure on the benthos at the only atoll in South Atlantic: Rocas atoll, NE Brazil. PLoS One 10, e0127176. http://dx.doi.org/10.1371/journal.pone.0127176.

Lopes, P.F.M., Mendes, L., Fonseca, V., Villasante, S., 2017. Tourism as a driver of conflicts and changes in fisheries value chains in marine protected areas. J. Environ. Manag. 200, 123–134. http://dx.doi.org/10.1016/j.jenvman.2017.05.080.

Luiz, O.J., Edwards, A.J., 2011. Extinction of a shark population in the archipelago of Saint Paul's rocks (equatorial Atlantic) inferred from the historical record. Biol. Conserv. 144 (12), 2873–2881. http://dx.doi.org/10.1016/j.biocon.2011.08.004.

Madin, E.M.P., Ban, N.C., Doubleday, Z.A., Holmes, T.H., Pecl, G.T., Smith, F., 2012. Socio-economic and management implications of range-shifting species in marine systems. Glob. Environ. Chang. 22 (1), 137–146. http://dx.doi.org/10.1016/j.gloenvcha.2011.10.008.

Magris, R.A., Heron, S., Pressey, R.L., 2015. Conservation planning for coral reefs accounting for climate warming disturbances. PLoS One(11), e0140828. http://dx.doi.org/10.1371/journal.pone.0140828.

Maynard, J.A., McKagan, S., Raymundo, L., Johnson, S., Houk, P., Williams, G.J., Kendall, M., Heron, S.F., 2015. Assessing relative resilience potential of coral reefs to inform management. Biol. Conserv. 192, 109–119. http://dx.doi.org/10.1016/j.biocon.

2015.09.001.

Mora, C., Sale, P., 2011. Ongoing global biodiversity loss and the need to move beyond protected areas: a review of the technical and practical shortcoming of protected areas on land and sea. Mar. Ecol. Prog. Ser. 434, 251–266. http://dx.doi.org/10.3354/meps09214.

Mora, C., Graham, N.A.J., Nystrom, M., 2016. Ecological limitations to the resilience of coral reefs. Coral Reefs 35 (4), 1271–1280. http://dx.doi.org/10.1007/s00338-016-1479-z.

Morais, G.W., Schluter, A., Verweij, M., 2015. Can institutional change theories contribute to understanding of marine protected areas? Glob. Environ. Chang. 31, 154–162. http://dx.doi.org/10.1016/j.gloenvcha.2015.01.008.

Morais, R.A., Ferreira, C.E.L., Floeter, S.R., 2017. Spatial patterns of fish standing biomass across Brazilian reefs. J. Fish Biol. http://dx.doi.org/10.1111/jfb.13482.

Mumby, P.J., 2017. Embracing a world of subtlety and nuance on coral reefs. Coral Reefs 36 (3), 1003–1011. http://dx.doi.org/10.1007/s00338-017-1591-8.

Mumby, P.J., Anthony, K.R.N., 2015. Resilience metrics to inform ecosystem management under global change with application to coral reefs. Method. Ecol. Evol. 6, 1088–1096. http://dx.doi.org/10.1111/2041-210X.12.380.

Neubauer, P., Jensen, O.P., Hutchings, J.A., Baum, J.K., 2013. Resilience and recovery of overexploited marine populations. Science 340, 347–349. http://dx.doi.org/10.1126/science.1230441.

Oesterwind, D., Rau, A., Zaiko, A., 2016. Drivers and pressures – untangling the terms commonly used in marine science and policy. J. Environ. Manag. 181, 8–15. http://dx.doi.org/10.1016/j.jenvman.2016.05.058.

Paiva, S.V., Oliveira Filho, R.R., Lotufo, T.M.C., 2015. Ascidians from Rocas atoll, Northeast Brazil. Front. Mar. Sci. http://dx.doi.org/10.3389/fmars.2015.00039.

Pereira, N.S., Manso, V.A.V., Silva, A.M.C., Silva, M.B., 2010. Mapeamento Geomorfológico e Morfodinâmica do Atol das Rocas, Atlântico Sul. J. Int. Coast. Zon. Manag. 10 (3), 331–345. http://dx.doi.org/10.5894/rgci209.

Pereira, N.S., Sial, A.N., Kikuchi, R.K.P., Ferreira, V.P., Ullmann, C.V., Frei, R., Cunha, A.M.C., 2015. Coral-based climate records from tropical South Atlantic: 2009/2010 ENSO event in C and O isotopes from Porites corals (Rocas atoll, Brazil). An. Acad. Bras. Cienc. 87 (4), 1939–1957. http://dx.doi.org/10.1590/0001-3765201520150072.

Pereira, N.S., Sial, A.N., Frei, R., Ullmann, C.V., Korte, C., Kikuchi, R.K.P., Ferreira, V.P., Kilbourne, H., 2017. The potential of the coral species *Porites astreoides* as a paleoclimate archive for the tropical South Atlantic Ocean. J. S. Am. Earth Sci. 77, 276–285. http://dx.doi.org/10.1016/j.jsames.2017.05.008.

Pinheiro, B.R., Pereira, N.S., Agostinho, P.G.F., Montes, M.J.F., 2017. Population dynamics of *Siderastrea stellata* Verrill, 1868 from Rocas atoll, RN: implications for predicted climate change impacts at the only South Atlantic atoll. An. Acad. Bras. Cienc. 89 (2), 873–884. http://dx.doi.org/10.1590/0001-3765201720160387.

Ross, R.E., Nimmo-Smith, W.A.M., Howell, K.L., 2017. Towards “ecological coherence”: assessing larval dispersal within a network of existing marine protected areas. Deep-Sea Res. I Oceanogr. Res. Pap. 126, 128–138. http://dx.doi.org/10.1016/j.dsr.2017.06.004.

Rossi, S., 2013. The destruction of the ‘animal forests’ in the oceans: towards an over-simplification of the benthic ecosystem. Ocean Coast. Manag. 84, 77–85. http://dx.doi.org/10.1016/j.ocecoaman.2013.07.004.

Sissini, M.N., Longo, G.O., Martins, C.D.L., Floeter, S.R., Pereira, S.B., Horta, P.A., 2014. First record of the green alga Halimeda (Bryopsidales: Chlorophyta) at Rocas atoll-natural dispersion or anthropogenic causes? Mar. Biodivers. Rec. 7, 1–5. http://dx.doi.org/10.1017/S1755267214001018.

Soares, M.O., Paiva, C.R., Godoy, T., Silva, M.B., Castro, C.S.S., 2010. Gestão Ambiental de ecossistemas insulares: O caso da reserva Biológica do Atol das Rocas, Atlântico Sul Equatorial. J. Integ. Coas. Zon. Man. 10 (3), 347–361. http://dx.doi.org/10.5894/rgci214.

Soares, M.O., Paiva, C.C., Godoy, T., Silva, M.B., 2011. Atol das Rocas (Atlântico Sul Equatorial): Um caso de Lixo Marinho em Áreas Remotas. J. Integ. Coas. Zon. Man. 11, 149–152. http://dx.doi.org/10.5894/rgci233.

Soares, M.O., Davis, M., Carneiro, P.B.M., 2016. Northward range expansion of the invasive coral (Tubastraea tagusensis) in the southwestern Atlantic. Mar. Biodivers. 1–4. http://dx.doi.org/10.1007/2Fs12526-016-0623-x.

Soares, M.O., Lotufo, T.M., Vieira, L.M., Mota, S.S., Hadju, E.C.M., Matthews-Cascon, H., Leão, Z.M.A.N., Kikuchi, R.K.P., 2017. Brazilian Marine Animal forests: a New world to discover in Southwestern Atlantic. In: Rossi, S. (Ed.), Marine Animal Forests: The Ecology of Benthic Biodiversity Hotspots of the World. Springer International Publishing Switzerland, pp. 73–110. http://dx.doi.org/10.1007/978-3-319-17001-5_51-1.

Standish, R.J., Hobbs, R.J., Mayfield, M.M., Bestelmeyer, B.T., Suding, K.N., Battaglia, L.L., Eviner, V., Hawkes, C.V., Temperton, V.M., Cramer, V.A., Harris, J.A., 2014. Resilience in ecology: abstraction, distraction, or where the action is? Biol. Conserv. 177, 43–51. http://dx.doi.org/10.1016/j.biocon.2014.06.008.

Tchamabi, C.C., Araújo, M., Silva, M., Bourlès, B., 2017. A study of the Brazilian Fernando de Noronha and Rocas atoll wakes in the tropical Atlantic. Ocean Model 111, 9–18. http://dx.doi.org/10.1016/j.ocemod.2016.12.009.

UNESCO, 2017. Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserve. Available in. http://whc.unesco.org/en/list/1000.

Woodroffe, C.D., 2008. Reef-island topography and the vulnerability of atolls to sea-level rise. Glob. Planet. Chang. 62 (1–2), 77–96. http://dx.doi.org/10.1016/j.gloplacha.2007.11.001.